

Engineering tool for the evaluation of global IED effects

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Abstract

The detonation of an IED near a military vehicle induces different damage effects on the vehicle and its occupants. There are local effects from fragments and projectiles but there are also global effects from a momentum transfer on the complete vehicle structure and a subsequent dynamical motion of the vehicle with phenomena like overturning or vehicle displacement from the road.

Questions like this can be answered with numerical finite-element simulations but there is also the need for engineering tools that allow a quick and nearly instantaneous simulation of these phenomena. The following work presents an approach for a fast analysis of global IED effects on vehicles. The physical modelling is based on analytical formula and empirical data that describe the momentum transfer of a detonation on a nearby structure. This momentum is the initial condition for the calculation of the following vehicle motion and the simulation of vehicle dynamics and jump height.

The software itself has a modern GUI that allows the generation of the vehicle structure and the threat scenario together with an interactive analysis of the simulation results.

The engineering tool is validated with small size generic vehicle tests where jump height and the vehicle motion are compared. The software allows a detailed analysis of global IED effects and can be additionally used in an inverse mode for the analysis of incidents with the determination of used HE masses in an IED attack.

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1. Introduction

Improvised explosive devices (IEDs) are today one of the most dangerous threats to military forces and their operational vehicles. IED threats cover a wide spectrum of scenarios ranging from explosive charges (military HE or homemade explosives) to projectile forming shells and HE filled munitions like grenades. The effects on a vehicle can be separated into local and global phenomena. There are local effects like penetration and perforation of fragments and projectiles, but there are also global effects connected with a high momentum transfer onto the vehicle and subsequent severe acceleration effects on the vehicle occupants [1,2].

During the time of more conventional military threat, protected vehicles were mostly exposed to effects from shallowly buried mines which showed well defined designs, burial condi-

tions and charge masses (up to 10 kg). Most interest was focused on the mission kill of the vehicle and for heavy tanks on the destruction of the tank tracks. Global effects on the vehicle as a whole were not considered. This changed with the appearance of deeply buried IED charges that contain significantly more HE which leads to high momentum transfer on the whole vehicle. The situation created the necessity for the analysis of the effects of buried charges on vehicle structures, especially for experimental and theoretical methods to predict the impulse transfer on the vehicle bottom. Experimental test methods were developed to measure and analyse the momentum transfer from unconfined and buried charges onto simplified generic structures, e.g. plates and cubes [3–7]. Of special importance are experimental results that include information about the spatial distribution of the specific momentum (Ref. 4 for buried charges and Ref. 5 for free charges including shape effects). Global momentum transfer and the influence of the embedding material is analysed in Ref. 3. A sand model including effects of moisture is presented in Ref. 6. The experiments were used to validate analytical and empirical models in the literature that

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were developed to quantify the impulse transferred from HE detonations [4,8]. On the other hand, numerical simulation models with detailed material descriptions for the embedding materials provided increasing knowledge about the details of the momentum transfer process, influence of embedding material and depth of burst. Adequate material and simulation models were necessary to describe correctly the load transfer from the detonation to the vehicle floor [2,6,7,9–11].

In previous papers, global IED effects and possible protection concepts were discussed [1,2,7,9]. This work is based on these results and summarises them in a form of an engineering software tool called PVIED (Protection of Vehicles against IED). The emphasis was put on modelling the momentum transfer from a buried IED detonation onto the vehicle structure. The physical models are based on analytical and empirical data. A test technology with generic small size vehicles was used for an extensive validation of the theoretical models. The software is equipped with a modern graphical interface for the generation of the vehicle structure and the definition of the threat scenario. This has the advantage of short response times compared with numerical FE-simulations of IED incidents. Different scenarios with varying IED placement conditions can be quickly analysed. The tool can thus be used for the detailed analysis of IED incidents (e.g. determination of the used high explosive mass). In addition it facilitates the design of experimental setups for the analysis of detonation effects on structures.

2. Validation tests with small vehicles

Validation tests of the effects of buried charges with real vehicles are very expensive. We therefore use a method with small size generic vehicles that are exposed under exactly defined conditions to detonation effects from buried HE

charges. Especially the preparation of the embedding conditions of the charge requires considerable attention. For this purpose we used a concrete pit with dimensions of $2\text{ m} \times 2\text{ m} \times 1\text{ m}$ as shown in Fig. 1. The pit will be filled with sand or gravel according to an exactly defined procedure (constant fall height and layer by layer). The material is changed after each test and the sand conditions are determined for each experiment (e.g. natural density, water content and saturation). The dynamical motion of the vehicle is recorded with redundant measurement techniques:

- 1) High speed camera (Photron with frame rate 1000 per second, captured time interval 1500 ms, optical determination of flight height and initial velocity with the help of the gauge grid shown in Fig. 1).
- 2) Accelerometers (measurement range $\pm 6000\text{ g}$, placed at different positions in the vehicle, recorded data for acceleration as a function of time, integration results in velocity and jump height).
- 3) Cable actuated position sensor (independent validation of jump height measurement).

This allows the determination of the momentum transfer and the following quasi free flight trajectory of the vehicle. The test set-up and a picture about 50 ms after the explosion of a buried charge are shown in Fig. 1. The global design parameters of the generic vehicle are: mass 150 kg, length 103.8 cm, height 53.8 cm, made of steel (plate thickness 6 mm), centre of gravity longitudinal 505 mm from the rear side, vertical 266 mm from the bottom of the wheels. The experimental results concerning global IED effects are momentum transfer, jump height and vehicle accelerations. The measurements from the tests are used to validate the presented engineering tool.

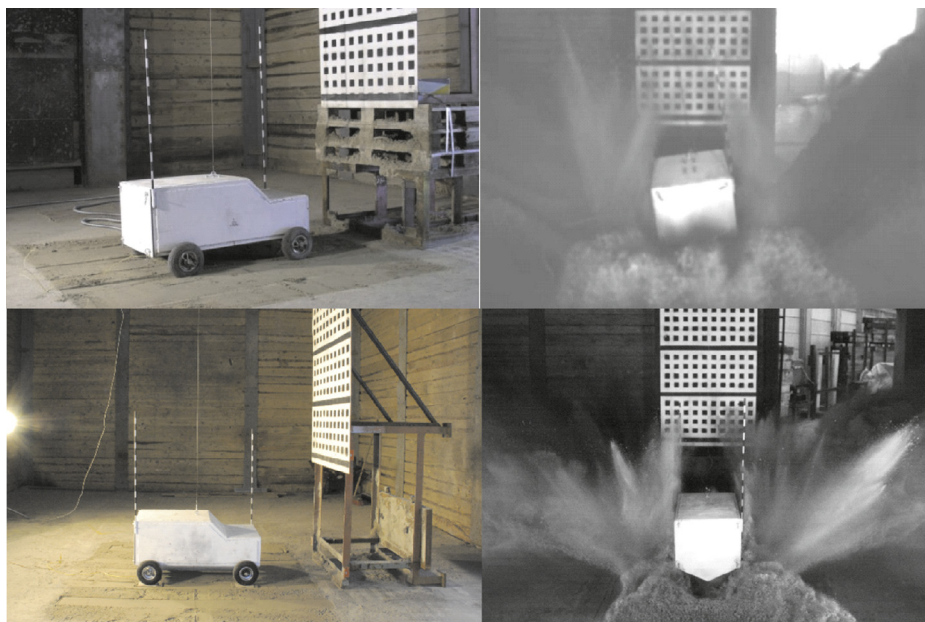


Fig. 1. Test set-up (left) with the small size vehicle (top: flat, bottom: V-shaped vehicle floor) and high-speed video camera pictures, about 50 ms after explosion (right).

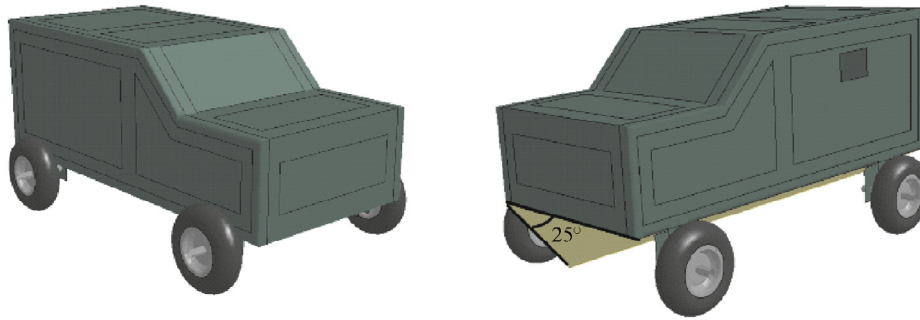


Fig. 2. FE-models of the generic model vehicles (left: flat, right: V-shaped hull).

3. Typical global vehicle loading condition during IED detonation

The momentum transfer from a buried IED charge onto a vehicle is strongly determined by the burial conditions (charge mass, depth of burial, nature of the embedding material). The embedding material serves as a mediator between the detonation products and the vehicle structure. The momentum transfer time is significantly shorter than the reaction time of the vehicle. The details of this process can be studied with the help of numerical simulations. The FE-models of our test vehicles (flat bottom and V-shaped bottom) are shown in Fig. 2. The selected generic burial conditions are: high explosive (HE) mass 200 g, positioned under the centre of gravity of the vehicle, sand emplacement and depth of burial of 12.5 cm. The simulations are performed with the finite-element software LS-DYNA. The vehicle is represented by a Lagrange model (30,000 shell elements), and the embedding material with the HE charge and the surrounding air are represented by an Euler model (1.2 million solid elements). The detonation process is simulated with a complete Euler–Lagrange coupling method. The time to perform the simulation is about 30 hours, with a parallelised computation on 16 cores. Special attention must be addressed to the material modelling of the embedding material. The model from Laine and Sandvik [11] for sand was used, which includes an equation of state for the compaction of the sand particles and a Mohr–Coulomb type model for the strength behaviour.

The corresponding simulation results for the momentum transfer onto the vehicle are summarised in Fig. 3 (velocity),

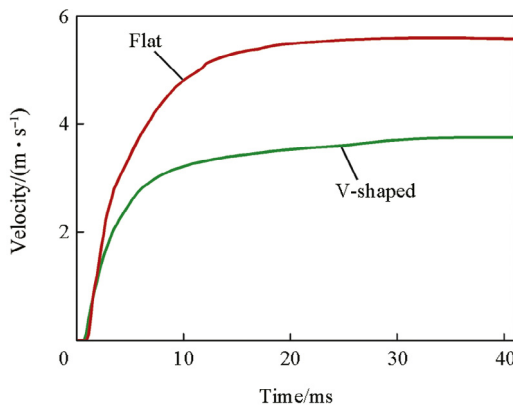


Fig. 3. Global vehicle velocity (scaled) after IED detonation.

Fig. 4 (acceleration) and Fig. 5 (vertical displacement). The peak value of the vehicle velocity is reached after less than 20 ms. The maximum acceleration is observed after 2 ms and falls off to a value less than 10% of the maximum value within 10 ms. The global motion of the vehicle starts significantly later (after 20 ms, the vehicle has just moved 5 cm upwards), which justifies an instantaneous momentum transfer from the IED detonation onto the vehicle structure. The modelling approach for the engineering tool is based on this assumption. A comparison between the numerical simulation with the finite element models, the simulation with the PVIED tool and the experiment is given in Fig. 14.

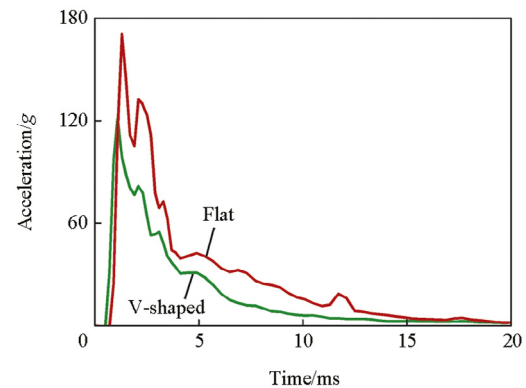


Fig. 4. Global vehicle acceleration (scaled) after IED detonation.

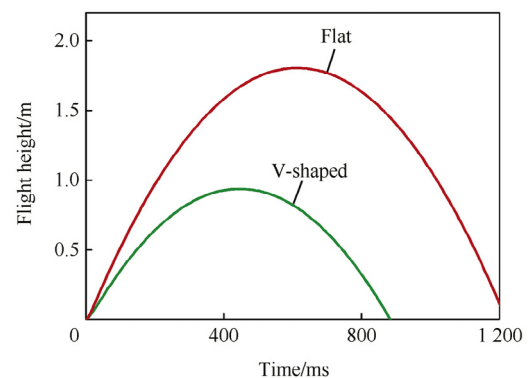


Fig. 5. Global vehicle jump height (scaled) after IED detonation.

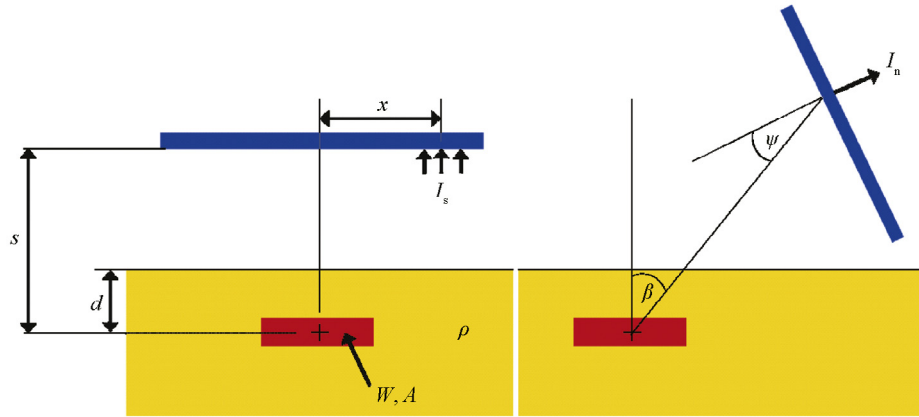


Fig. 6. Geometrical configuration for a flat (left) or an inclined (right) plate above a buried charge.

4. Modelling approach

The engineering tool distinguishes the detonation of an unconfined charge with the corresponding development of the blast wave in air from the detonation of a buried charge as described in Chapter 3. The effect of a blast wave in air is well characterised in the literature [12]. The profile of the wave with the characteristic parameters maximum pressure, duration of the wave and specific momentum is tabulated as a function of distance and directly implemented into the engineering code. The blast parameters are given with reference to TNT. Other types of explosive are treated with the corresponding TNT equivalent factor for the impulse. For our application, the specific momentum in a given distance to the charge is of main importance. The engineering tool covers the vehicle structure with a grid pattern and calculates for each grid point the distance to the charge. With the tabulated blast parameters, the transfer of momentum can be calculated as the sum over all grid points and serves as the starting condition for the dynamic motion of the vehicle under the influence of gravity.

A similar approach was taken for the case of buried charges. The specific momentum is based on an analytical empirical approach (see Ref. 8) where the local distribution of the specific impulse on a flat plate as a function of the burial parameters is given (the charge shape is cylindrical with the symmetry axis perpendicular to the ground surface).

Fig. 6 shows the geometrical configuration together with the parameters that define the burial configuration (see Table 1). Important parameters are the charge mass and distances defining the geometry. Analytical expressions given in Ref. 8 allow the calculation of the specific momentum I_s as a function of these parameters. The corresponding formulae are summarised in Eqs. (1)–(3)

$$Z = \frac{xd}{s^{5/4} A^{3/8} \tan h \left(2.2 \frac{d}{s} \right)^{3/2}} \quad (1)$$

$$Y = \frac{0.1352 \tan h^{3.25} (0.9589 Z)}{Z^{3.25}} \quad (2)$$

$$I_s = \frac{Y \sqrt{\rho W} \left(1 + \frac{7d}{9s} \right)}{\sqrt{s}} \quad (3)$$

It should be mentioned that the type of explosive enters not explicitly but with the parameter W that corresponds to the energy release of the used IED charge.

As mentioned in Ref. 13, the Westine formulae are experimentally validated within a certain range defined by four nondimensional parameters. Table 2 gives these boundaries, as well as typical values for our testing cases (200 g TNT, 125 mm depth of burial), and typical loading cases for real IED incidents (40 kg TNT and 100 kg). All cases are within the validity range of the Westine formulae.

Table 1
Definition of the parameters for Eqs. (1)–(3).

| Parameter | Description/Unit |
|-----------|--|
| Y | Scaled impulse/– |
| Z | Scaled distance/– |
| s | Distance from the steel plate to the centre of the charge/mm |
| d | Depth of burial (until the centre of the charge)/mm |
| x | Lateral distance to the centre of the plate/mm |
| I_s | Specific impulse/(kPa·ms) |
| W | Energy released by the charge/mJ |
| A | Upper surface of the charge/mm ² |
| ρ | Soil density/(g·mm ^{−3}) |

Table 2
Validity range of the Westine formulae for three test cases (200 g, 40 kg and 100 kg TNT, c: seismic P-wave velocity of the soil).

| | 200 g TNT | 40 kg TNT | 100 kg TNT | Upper boundary |
|--------------------------------------|--------------|--------------|---------------|-------------------|
| d/s | | | | |
| 0.11 | 0.5 | 0.54 | 0.69 | 1 |
| $(W/A)/(\rho \text{ c}^2 \text{ s})$ | | | | |
| 6.35 | 6.37 | 9.56 | 8.7 | 150 |
| \sqrt{A}/s | | | | |
| 0.15 | 0.25 | 0.37 | 0.25 | 4.48 |
| x/s | | | | |
| 0 | 3.62 | 0.93 | 3.62 | 19.3 |

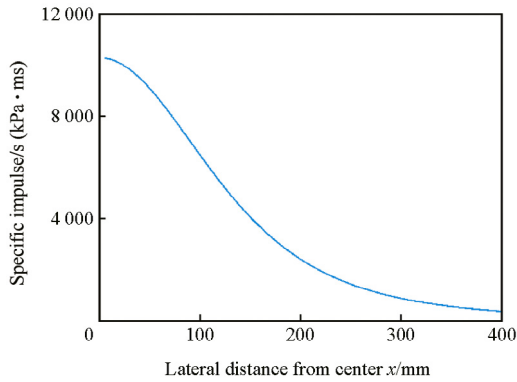


Fig. 7. Specific impulse as a function of lateral distance to the charge centre.

The generalisation to inclined plates was done in Ref. 14 (the geometrical configuration is shown in Fig. 6) and leads to the following formula (Eq. 4) for the specific impulse I_N normal to the plate (the definition of the angles ψ and β is given in Fig. 6)

$$I_N = I_s \frac{\cos(\psi)}{\cos(\beta)} \quad (4)$$

The characteristic behaviour is the exponential decay of the impulse with increasing distance to the charge centre (an example is given in Fig. 7, for a charge of 200 g TNT in sand, with a depth of burial of 125 mm and the steel plate placed 200 mm above the ground). The momentum transfer determined from the presented equations is the initial condition for the following dynamical motion of the vehicle. This approach is based on experimental data and the accuracy of this model has major influence on the accuracy of the engineering tool. The validated parameter range is given in Ref. 15 and includes typical conditions occurring in IED threats. Most inaccuracy is caused by undefined or not well known burial conditions with possible deviations of up to 30% (see Ref. 13).

Experimental tests showed that the impulse transfer increases strongly with increasing soil moisture content [16]. In order to take into account this effect a correction factor was defined to modify the specific impulses calculated with the above presented formulae. The correction factor is given in Fig. 8 and is based on experiments from Ref. 16. The water

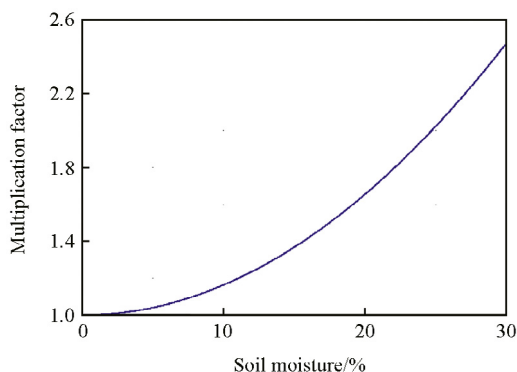


Fig. 8. Empirical correction factor for wet soil.

content of the embedding sand was varied between 0 and 30%. The specific impulse calculated in the PVIED tool is thus obtained by multiplying the specific impulse from Eq. (4) with this empirical correction factor that takes into account the water content of the embedding material.

5. Engineering tool PVIED

The presented physical models and empirical data are implemented in the engineering tool PVIED. The graphical interface of the software is shown in Fig. 9. The tool is built up of the following 4 sub menus:

- 1) Generation of vehicle geometry,
- 2) Definition of incident scenario,
- 3) Run of simulation,
- 4) Analysis of results.

As an example Fig. 9 shows the model of the scaled test vehicle that was described in Chapter 2. The generation of the vehicle structures starts with a model of the 2D cross section on the left side of the graphical interface. In a second step an extruding process generates a 3D-model where additional components as V-shaped undercarriage and engine can be added. The IED is defined by the explosive mass, explosive type and position and is indicated by the red disc on the graphical interface. The underground can be defined as a soil type with given density and water content but also as a road surface consisting of concrete plates with given thickness and lateral dimensions.

The model equations from Chapter 4 are used to calculate the momentum transfer onto the vehicle structure. As shown before this process occurs on a very short time scale compared with the following rigid body motion of the vehicle. The induced momentum thus serves as an initial condition for the following motion of the vehicle. A multi-body dynamics solver that was originally developed for game software (see Ref. 17) was selected for the simulation of the dynamic motion of the vehicle in the gravitational field including interactions with other objects (e.g. road surface). The analysis gives information about jump height and final position of the vehicle and components on the ground surface. The graphical interface allows a detailed analysis of the vehicle trajectory together with an animation of the vehicle motion.

An example for the calculation of the specific momentum distribution on a vehicle floor from the detonation of a buried IED is shown in Fig. 10 (charge mass of 200 g). For this case, the two small size test vehicles presented in Chapter 3 were chosen. One vehicle has a flat floor, while the other vehicle shows a V-shaped floor. The local specific momentum distribution from the IED detonation is shown in Fig. 10. Although the loading comes from a buried charge, the momentum transfer is still rather localised on the floor. A quantitative analysis together with the experimental results is given in the next chapter.

The used physics solver is able to simulate multi-body interaction between different objects. This property can be used for the analysis of vehicle borne IEDs (VBIED). In this case the explosive charge is placed inside the vehicle with subsequent momentum transfer onto the vehicle structure and massive components like engine and axis. Failure or breakup

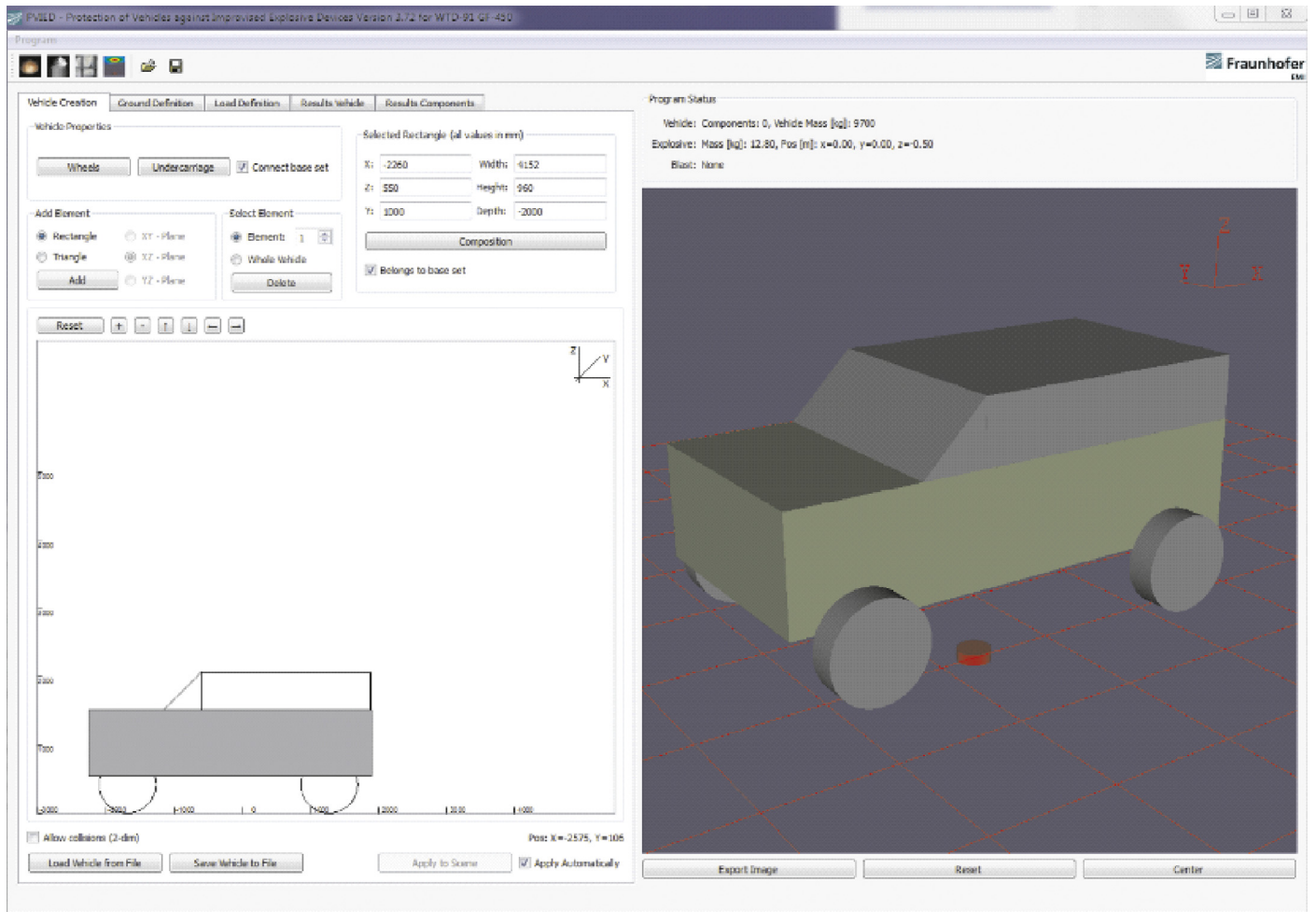


Fig. 9. Graphical user interface of the engineering software PVIED with the model of the generic test vehicle.

of the structure is not modelled; it is assumed that the energy for this process is smaller than the kinetic energy transferred to the vehicle components. The dominant process especially for larger charges is the multibody interaction after the charge detonation. The following interaction of these vehicle components leads to a specific distribution of debris that can be used for the analysis of incidents in operational areas. An example of the use of the PVIED tool for this application is

given in Fig. 11 for a truck, with an explosive charge (mass 5 kg) placed at the centre of the container. The location of massive components (e.g. engine block with mass of 500 kg) after the detonation can be used as indicator for the deposited IED charge mass. In this case the engine block showed a displacement of about 3.5 m. Parametric variations of the burial conditions with the PVIED software thus can serve as an inverse tool for the incident analysis.

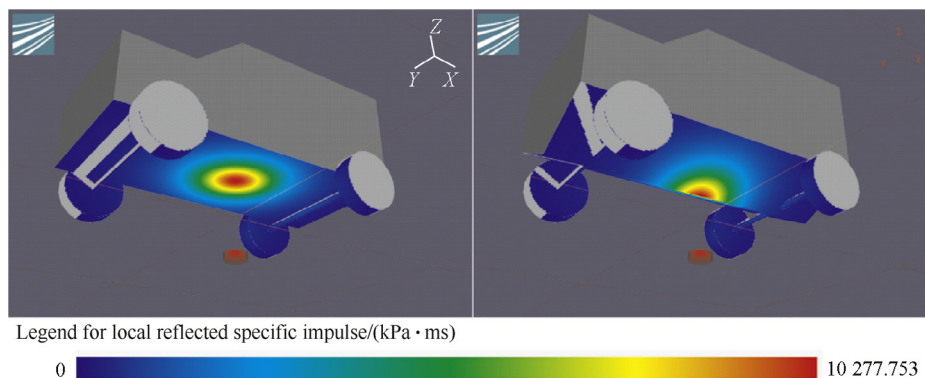


Fig. 10. Typical specific momentum distributions on a flat (left) and a V-shaped (right) vehicle floor.

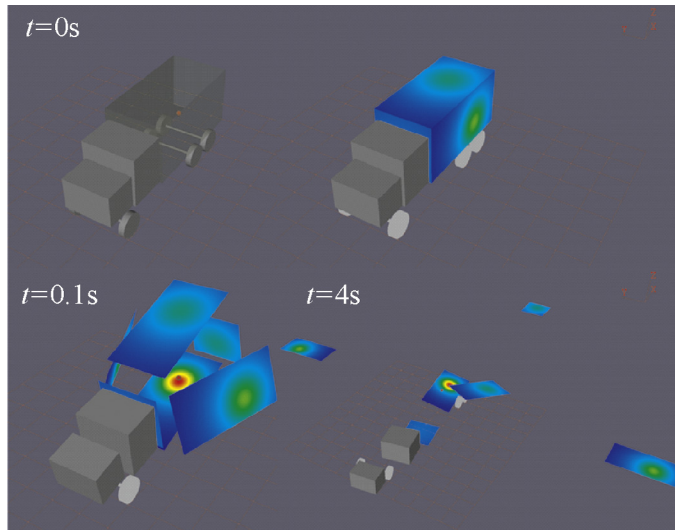


Fig. 11. Example of a vehicle Borne IED explosion.

6. Validation of PVIED

The validation was done with experiments that used the small generic vehicles presented in Chapter 2. Two different vehicle designs were chosen: one with a flat floor and the second with a V-shaped floor. In the actual burial

configuration, a high explosive mass of 200 g in a sand environment was used. Details about the test set-up and the experimental determined parameters were given in Chapter 2 (see Fig. 1). Experimental results and the corresponding PVIED simulations are shown in Fig. 12 with a comparison of the vehicle position at the times 430 ms (V-shaped) and 600 ms (flat) which are approximately the times with maximum flight heights of the vehicle. It is obvious that the V-shaped vehicle shows a significantly lower momentum transfer compared to the flat vehicle.

A more detailed quantitative comparison of the experiment and simulation is shown in Fig. 13 where the time history of the flight height of the vehicles is presented. The maximum height of the V-shaped vehicle is only half of the value for the flat vehicle. This corresponds to a reduction of the momentum transfer of about 25%. The curves for the jump height from the PVIED simulation can be directly compared with the experimental results. The simulation is generally higher than the experiment with deviations between 13% (flat vehicle) and 32% (V-shaped vehicle).

A summary of the complete transferred momentum onto the flat and the V-shaped vehicles of the experimental results and the simulation results (PVIED and FE simulations) is given in Fig. 14. The experimental results show that the momentum

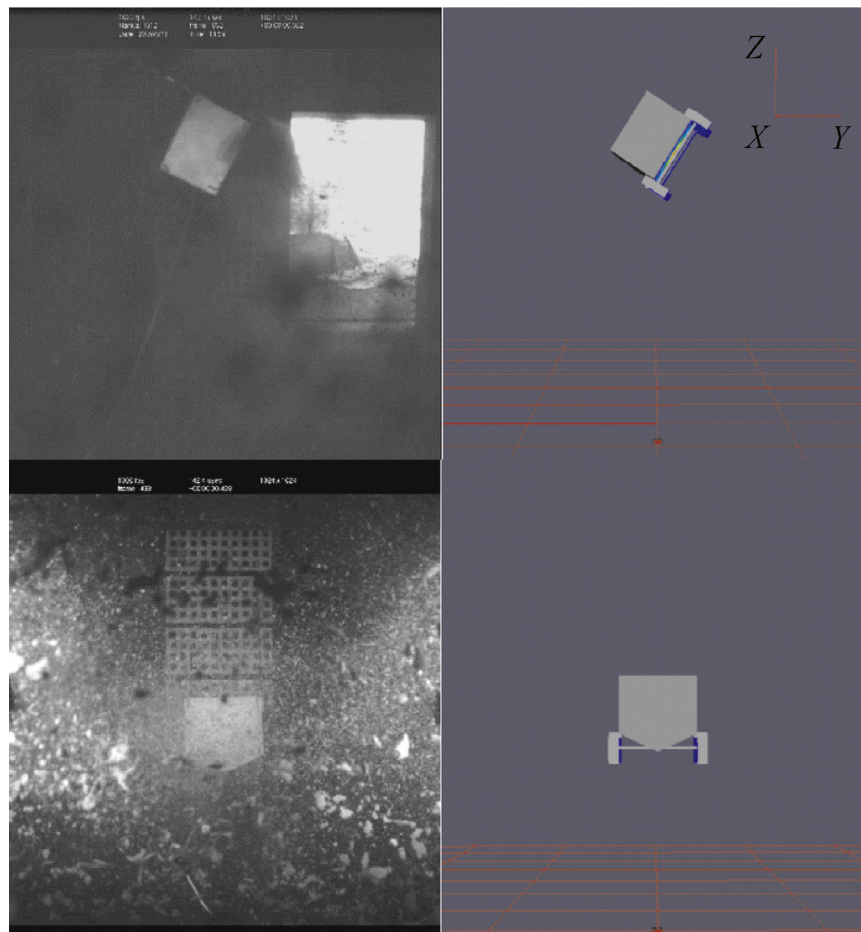


Fig. 12. Validation of engineering approach with testing results (top: flat, bottom: V-shaped hull, left: experiment, right: PVIED tool).

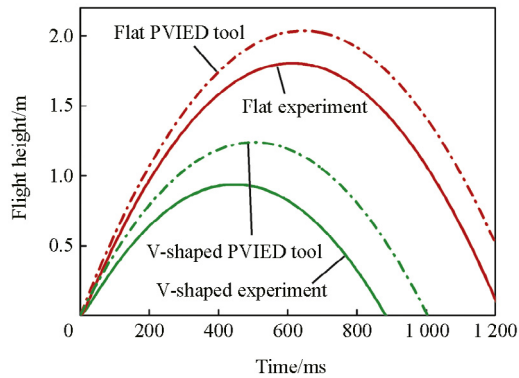


Fig. 13. Validation of the PVIED tool with scaled IED tests (jump height).

transfer onto the V-shaped vehicle is about 25% smaller compared to the flat vehicle. The PVIED simulation reproduces this effect very well. In general the PVIED simulation gives values that are roughly 10% higher than the experimental results. The finite element simulation gives values that are between 2% (flat vehicle) and 13% lower (v-shaped vehicle) than the experimental results.

This agreement is good enough to justify the use of the engineering tool PVIED to obtain first and quick but still reliable results for global IED effects from buried charges.

7. Summary

- 1) An engineering tool was presented that allows the analysis of global IED effects on vehicles. The software gives information about the momentum transfer, jump height, overturning and motion of the vehicle in the earth gravity field. The simulation time is very fast, within several seconds, and makes parametric studies easy performable. The tool possesses an interactive GUI for the generation of the vehicle model, the threat scenario and the analysis of the generated data.
- 2) The physical modelling approach for the description of global IED effects is based on analytical formula and empirical data that are implemented in the software. They allow the calculation of the transferred momentum and the simulation of the following dynamical vehicle motion. The vehicle flight trajectory and possible interactions with other objects are simulated with a multi-body dynamics solver that is originally used for the development of game

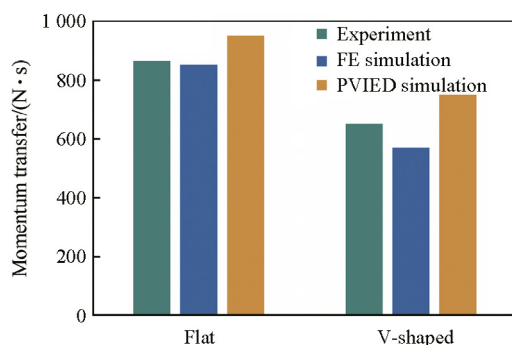


Fig. 14. Validation of the PVIED tool with test results and finite element simulations (momentum transfer).

software. To a certain extent PVIED can be used for the analysis of IED incidents. Starting with a scenario after an IED attack, an inverse optimisation procedure allows the estimation of the burial conditions and the determination of the mass of the used HE.

- 3) The software was validated with small size generic vehicle experiments. For this purpose well instrumented tests with different charges and burial conditions were performed and the subsequent motion and jump height of the vehicle were recorded. The experimental results were compared with the results from the tool and showed, for the purpose of an engineering tool, very good agreement.

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